

CHAPTER 5

EFFECTS OF SMALL PARTICLES AND BIOLOGICAL MATTER

5.1 CLOUDS AND FOG

5.1.1 introduction

Clouds, dust, and vegetation and their effects on propagation are the principal topics considered in this chapter. Clouds and fog are both composed of minute water droplets or ice crystals suspended in air. Fog forms near the Earth's surface, and clouds occur at higher levels. Both clouds and fog form through cooling, clouds when air cools adiabatically while rising for example and fog by contact and mixing. Fog also sometimes forms by increase of water content. Clouds are of three basic types - cirrus, cumulus, and stratus (Dorm, 1975).

Cirrus clouds are high, thin, separated or detached clouds. They usually form above about 9 km (about 30,000 ft) and consist of thin crystals or needles of ice rather than liquid water. Cumulus clouds are the majestic clouds of summer- and fair weather generally. Their base is typically flat and they have considerable vertical extent. Stratus clouds have a large horizontal extent covering all or most. of the sky and showing little structure. They tend to have a uniform grey color. If a cumulus or stratus cloud occurs above its normal level, the term *alto* precedes the name. If a cloud is associated with rain, the term *nimbus* may be added to the basic name. Thus *nimbostratus* clouds are rain or snow clouds, and *cumulonimbus* clouds, which develop from cumulus clouds, are the clouds of thunderstorms. Clouds combining the characteristics of two of the basic types have names such as *stratocumulus* and *cirrostratus*.

Drop sizes and liquid water contents in *cumulonimbus* clouds are given in Table 5.1, adapted from Ludlam (1980). The table show values of drop concentration N , mass density p , and mean radius r for particular *cumulonimbus* clouds, which have relatively large values of liquid water content. The entries are arranged in groups or classes.

Table 5.1 Parameters of Cumulonimbus Clouds
(adapted from Ludlam, 1980)..

Class	N/cm ³	ρ (g/m ³)	r(μ m)
a	290	0.05	3.45
	590	0.13	3.74
	281	0.65	8.2
b	30	0.03	6.2
	41	0.025	5.26
	85	0.06	5.52
c	229	0.60	8.56
	182	0.95	10.76
	285	0.66	8.21
	220	0.51	8.21
	119	0.70	11.2
d	195	1.6	12.5
	99	5.0	22.9

Fog has four principal categories - radiation fog, advection fog, frontal fog, and upslope fog. Radiation fog forms when the Earth, and the air immediately above it, cools on clear nights. Advection refers to horizontal movement, and advection fog forms when cold air passes over a warm sea surface and when warm moist air passes over a cold surface. The latter mechanism is responsible for about 4/5ths of all maritime fogs (Dorm, 1975). Frontal fog is important over the continents and results at a front where warm air moves over cold air. Clouds form in the warm air, and if rain falls from the clouds it will add moisture to the cold air underneath which may already have been humid and near the dew point. The result is the formation of fog in the cold air. Upslope fog forms when humid air ascends a gradually sloping plain as in the interior plains of the United States. Ice fog forms at low temperatures in the order of -34 deg C (-30 deg F) and lower and is aggravated by manmade pollution. Ice fog is a problem in winter in Fairbanks, Alaska (Benson, 1965, 1970).

5.1.2 Rayleigh Scattering

The water droplets of clouds are small compared to wavelength, and Rayleigh scattering theory applies. Relations for η the radar cross section per unit volume; α , the attenuation constant; and β , the phase constant for clouds can be derived by using this theory. A suitable starting point is Laplace's equation $\nabla^2 \Phi = 0$ (Ramo, Whinnery, and Van Duzer, 1965), where Φ is scalar electric potential. Although Laplace's equation applies to static fields and we deal here with time-varying conditions, the equation can be applied to the small spherical droplets of clouds in the first stage of analysis because negligible phase shift occurs throughout these droplets.

For the case of a sphere, when no variation with the coordinate ϕ occurs, the solution of Laplace's equation for Φ_1 , the potential inside the sphere, is given in spherical coordinates by

$$\Phi_1 = \sum_{n=0}^{\infty} A_n r^n P_n(\cos \theta) \quad (5.1)$$

where r is the radial coordinate, θ is the polar coordinate, and $P_n(\cos \theta)$ is the Legendre polynomial of order n . Outside the sphere

$$\Phi_2 = \sum_{n=0}^{\infty} B_n r^{-n-1} P_n(\cos \theta) - E_0 r P_1(\cos \theta) \quad (5.2)$$

where the second term accounts for the applied field E_0 . At $r = a$ where a is drop radius, the two expressions can be equated so that

$$(\Phi_1)_{r=a} = (\Phi_2)_{r=a} \quad (5.3)$$

A_n and B_n are coefficients which need to be determined. For a particular value of n , Eq. (5.3) constitutes one equation for two unknowns. A second equation is obtained from

$$(D_{n1})_{r=a} = (D_{n2})_{r=a} \quad (5.4)$$

where D_n stands for the normal component of electric flux density in

coulombs/square meter. The values of electric flux density D are related to potential Φ by $E = -\nabla\Phi$ and $D = \epsilon K_0 E$ where E is electric field intensity, K is relative dielectric constant, and ϵ is the electric permittivity of empty space. The value of K in air outside the drop can be taken as unity, but K is complex and has a magnitude other than unity inside the drop. It turns out that only A_1 and B_1 have nonzero values. All the other A 's and B 's are zero, and solving for A_1 and B_1 is straitforward. It is B_1 that is of most interest because it gives the field quantities outside the drop. It is found that

$$B_1 r^{-n-1} P_n(\cos \theta) = (E_0 a^3/r^2) \left[\frac{K_c - 1}{K_c + 2} \right] \quad (5.5)$$

Comparing this form with that for an electric dipole (consisting of + and - charges separated by a distance d), it can be seen that a small water drop has an electric dipole moment p_1 given by

$$p_1 = 3 V \left[\frac{K_c}{K_c + 1} \right] \epsilon_0 E_0 \quad (5.6)$$

where $V = (4/3)\pi a^3$ is the volume of the drop. Note that K has become K_c with the subscript c indicating a complex quantity.

Thus under the influence of an applied field E , each water droplet is an elementary antenna that radiates energy, and the radiated field can be found by using antenna theory. Knowing the electric dipole moment of the antenna, it is convenient to use the Hertz potential Π , as described in Panofsky and Phillips (1955) for example, to calculate the radiated field intensity E_θ , where θ is measured from the direction of the incident field intensity E_0 . The radiated field intensity includes terms decreasing as $1/r$, $1/\lambda$, and $1/r^3$, but interest lies in the far-field solution and only the term varying as $1/r$ need be determined. Of course, at this stage the time varying nature of the field quantities is taken into account. The dipole moment p_1 of Eq. (5.6) radiates a far field E_θ given by

$$p_e = (3\pi V/\lambda^2 r) \left| \frac{K_c - 1}{K_c + 2} \right| \quad (5.7)$$

and from this expression it is possible to determine a radar cross section σ for a drop by recognizing that

$$P(\pi) = P_{inc} \sigma / 4\pi r^2 \quad (5.8)$$

where P_{inc} is the incident power density and equals E_o^2/η' and $P(\pi)$ is the radiated power density at an angle of π radians or 180 deg from the direction of the incident wave and equals \hat{E}_θ^2/η' . The quantity η' is the characteristic impedance of the medium. Equation (5.8) shows that the drop extracts energy from the incident wave in proportion to σ and is assumed to radiate this energy uniformly over a sphere of radius r , thus ignoring the variation of radiated field intensity with θ . Solving for σ , one obtains

$$\sigma = \pi^5/\lambda^4 \left| \frac{K_c - 1}{K_c + 2} \right|^2 d^6 \quad (5.9)$$

where d is drop diameter. To obtain η the radar cross section per unit volume, one sums for all the drops in a cubic meter to obtain

$$\eta = \pi^5/\lambda^4 \left| \frac{K_c - 1}{K_c + 2} \right|^2 \sum d^6 = \pi^5/\lambda^4 \left| \frac{K_c - i}{K_c + 2} \right|^2 z \quad (5.10)$$

The other two quantities of interest in this section are α and β , the attenuation and phase constants respectively. To obtain expressions for these, return to the expression for p_i , Eq. (5.6), and make use of the relation from field theory,

$$D = \epsilon_0 E + P = \epsilon_0 K_m E = \epsilon_0 (1 + \chi) E \quad (5.11)$$

where D is electric flux density (C/m^2), E is electric field intensity (V/m), and P is electric dipole moment per unit volume. Here we use K_m to stand for the complex relative dielectric constant of the medium consisting of water droplets in empty space, whereas K_c of Eq. (5.5), etc. stands for the relative dielectric constant of water. The quantity P is found from p_i by multiplying by the number of drops N per unit volume, assuming all drops to be of equal size and having the same dipole moment. That is

$$P = N p_i = 3 N V \left[\frac{K_c - 1}{K_c + 2} \right] \epsilon_0 E. \quad (5.12)$$

The complex index of refraction of the medium of water droplets in space, m_c , can be found from

$$m_c^2 = 1 + \frac{P}{\epsilon_0 E_0} = 1 + 3 N V \left[\frac{K_c - i}{K_c + 2} \right] \quad (5.13)$$

The other quantity χ of Eq. (5.11) stands for electric susceptibility and by comparing the two right-hand forms of Eq. (5.11), it is evident that

$$K_m = 1 + \chi \quad (5.14)$$

As we deal with empty droplets in empty space, χ is much less than unity and m_c is given by

$$m_c \approx 1 + \chi/2 = m_r - j m_i \quad (5.15)$$

Knowing m_c , α and β can be found from

$$a = m_i \beta_0 \quad Np/m \quad (5.16)$$

and

$$\beta = m_r \beta_o \quad \text{rad/m} \quad (5.17)$$

where β_o is the phase constant of empty space, α is the field intensity attenuation constant of the medium, and β is the phase constant of the medium.

An alternative approach for determining m_c is to use Eq. (4.9) but apply it to particles of fixed size. For the case that $\lambda \gg a$, where a is radius, So has the form of $j\beta_o [(K_c - 1)/(K_c + 2)] a^3$ (van de Hulst, 1957). Using Eq. (4.9) with S_o as indicated gives a result for m_c that is identical to that obtained above.

5.1 . 3 Attenuation

Numerical values of the power attenuation constant for clouds α_p , where $a_p = 2a$, can be found by using

$$\alpha_p = \left\{ 0.4343 \frac{6\pi}{\lambda} \text{Im} \left[- \frac{K_c - 1}{K_c + 2} \right] \right\} \rho_l \quad \text{dB/km} \quad (5.18)$$

where λ is wavelength in cm, I_m indicates the imaginary part of, K_c is the complex relative dielectric constant of water, and ρ_l is the water content of the cloud in g/m^3 . The quantity K_c is a function of temperature and frequency. It has the value of $78.45 - j11.19$ for $T = 20 \text{ deg C}$ and $\lambda = 10 \text{ cm}$, for example. Table 5.2 shows values of the imaginary part of $-(K_c - 1)/(K_c + 2) = -R$, adapted from Battan (1973) and originally provided by Gunn and East (1954). Equation (5. 18) can be used for ice as well as water

clouds if the density of ice is taken as 1 g/cm^3 . Equation (5. 18) follows from Eqs. (5.11) through (5. 16), if it is recognized that

$$N V \rho_w = N V 1000 = (\rho_l) \text{ kg/m}^3 \quad (5.19)$$

where N is the number of drops per cubic meter, V is the volume of a drop, ρ_w is the density of water (1000 kg/m^3), and ρ_l is the weight of liquid water in clouds in kg/m^3 . If ρ_l is to be in g/m^3 , however, note that

$$(\rho_l) \text{ g/m}^3 = 1000 (\rho_l) \text{ kg/m}^3 = 10^6 N V$$

Thus if $(\rho_l) \text{ g/m}^3 = 1$, $N V = 10^{-6}$. In general NV should be assigned the value of $10^{-6} (\rho_l) \text{ g/m}^3$. By multiplying the numerator and denominator of $[- (K_c - 1)/(K_c + 2)]$ of Eq. (5.18) by the complex conjugate of the denominator it can be shown that

$$\text{Im} \left\{ - \left[\frac{K_c - 1}{K_c + 2} \right] \right\} = \frac{3K_i}{(K_r + 2)^2 + K_i^2} \quad (5.20)$$

An alternative expression for attenuation in a cloud for frequencies from 1 to 50 GHz that does not require knowledge of K_c has the following form (Staelin, 1967).

$$\alpha_p = \frac{(4.343 \rho_l \cdot 10^{0.0122 (292-T)})^{-1}}{\lambda^2} \quad (5.21)$$

The quantity T is temperature in kelvins and equals 273 plus the temperature in deg C, λ is wavelength in cm, and ρ_l is water content in g/m^3 .

Values for total attenuation at frequencies of 2.3, 8.5, 10, and 32 GHz as calculated by Slobin (1981) are included in Table 5.3. The model utilized for calculations includes cloud layers having total thickness as shown and also includes the contributions to attenuation due to water vapor and oxygen as well as the larger contributions of water droplets. Values for the combined effect of water vapor and oxygen in a clear atmosphere are also shown for reference (the entry for $\rho_l = 0$). The condition of $\rho_l = 1 \text{ g/m}^3$ and a total cloud thickness of 4 km is referred to as a worst case, but it is possible for values of water content as great as 6 g/m^3 or more to occur. See Table 7.1 for a more complete listing, Fig. 9.15 for a map of cloud regions of the United States, and Slobin (1982) for further information.

Table 5.3 shows that attenuation due to clouds at frequencies of 10 GHz and lower is small. It should be noted, however, that the overall effect on signal-to-noise ratio involves both attenuation and the accompanying increase system noise temperature. Also note that the attenuation values are for a zenith path. For the worst case shown in Table 5.3 but for an elevation angle of 10° , the attenuation is $0.457 / \sin 10^\circ = 0.457 / 0.174 = 2.63 \text{ dB}$. Finally the view is taken here that the designer should know closely the magnitudes of the various effects even when they are small.

Table 5.2 Im (-R), adapted from Battan "(1973).

Substance	T(°C)	Im (-R), $\lambda = 10$ cm	Im (-R), $\lambda = 3.21$
Water	20°	0.00474	0.01883
	10°	0.00688	0.0247
	0°	0.01102	0.0335
Ice	0°	9.6×10^{-4}	9.6×10^{-4}
	-10°	3.2×10^{-4}	3.2×10^{-4}
	-20°	2.2×10^{-4}	2.2×10^{-4}

$R = (K_c - 1)/(K_c + 2)$, where K_c is the complex relative dielectric constant.

Table 5.3 Values of Attenuation and Contributions to Noise Temperature of Cloud Models.

ρ_L g/m ³	Total Thick- ness km	S-Band (2.3 GHz) Zenith		X-band (8.5 GHz) Zenith		X-band (10 GHz) Zenith		K _a -Band (32 GHz) Zenith	
		T(K)	A(dB)	T	A	T	A	T	A
0.5	2	2.43	0.040	6.55	0.105	8.25	.133	61.00	1.083
0.7	2	2.54	0.042	8.04	0.130	10.31	.166	77.16	1.425
1.0	2	2.70	0.044	10.27	0.166	13.55	.216	99.05	1.939
1.0	3	3.06	0.050	14.89	0.245	19.66	.326	137.50	3.060
1.0	4	3.47	0.057	20.20	0.340	26.84	.457	171.38	4.407
.0	0	2.15	0.035	2.78	0.0045	3.05	.049	14.29	0.228

5.1.4 Noise

The contributions to system noise temperature due to clouds, water vapor, and oxygen (primarily clouds) are shown in Table 5.3 also. For considering these values, Eq. (3.25) is repeated below.

$$T_b = T_s e^{-\tau} + T_i (1 - e^{-\tau}) \quad (5.22)$$

The equation applies to the brightness temperature T_b when a source at a temperature of T_s is viewed through an absorbing region having an effective temperature of T_i . The parameter τ represents optical depth, namely the integral of the power attenuation constant along the path. In the case considered here, the first term has a small value and will be neglected. Values of T_i generally range from about 260 K to 280 K. If values for T_i and τ are known or can be assumed then T_b can be calculated.

For example, assume an attenuation of 1 dB and a value of 273 K for T_i . Then noting that

$$A_{\text{dB}} = 10 \log L = 10 \tau \log_{10} e = 4.343 \tau \quad (5.23)$$

where A is attenuation and $L = 1/e^{-\tau}$, $\tau = 1/4.343$, $e^{-\tau} = 0.794$, and $T_b = 56$ K. An attenuation of only 1 dB is seen to be associated with a fairly large contribution to system noise temperature. The subject of noise is treated more fully in Chap. 7. Attenuation and noise due to clouds are modest but not insignificant at frequencies of 10 GHz and lower. Table 5.3 includes entries for 32 GHz which illustrate the fact that the effects of clouds are more serious at higher frequencies.

5.1.5 Range Delay

In Sec. 3.7, the excess range delay due to dry air and water vapor was considered. Liquid water in the form of clouds and the larger drops of rain may also make a contribution to range delay. The basis for analyzing the delay due to the liquid water of clouds was developed in Sec. 5.1.2, and Eq. (5. 17) for the phase constant of a medium consisting of water droplets in otherwise empty space is applicable. The excess range delay, however, is determined by the difference between the real part of the index of refraction and unity. Thus AR due to clouds is given by

$$\Delta R = \int \text{Re} (m_c - 1) dl = \int (m_r - 1) dl \quad (5.24)$$

Taking the real part m_r of m_c and subtracting unity as indicated in the equation and considering the case of a constant value of m_r over a length L leads to the expression

$$AR = (m_r - 1)L = \frac{2}{3} \left[\frac{K_r^2 + K_i^2 + K_r - 2}{(K_r + 2)^2 + K_i^2} \right] L \quad (5.25)$$

This equation can be applied to cloud models to determine representative value of AR.

To illustrate the range delay caused by water droplets in a cloud, consider the delay for a zenith path through a cloud 1 km thick and having a water content of 1 g/m³. For a frequency of 3 GHz and a temperature of 20 deg C, it can be determined from curves given by Jeffery (1972) that $n_c = 8.88 - j0.63$ for water. As water has a density of 1 g/cm³, the water content of 1 g/m³ fills only 10⁻⁶ of a m³. Then N of Eq. 5. (13) is 10⁻⁶ and it develops that

$$\text{Re} (m_c - 1) = 3/2 \cdot (0.967) \cdot 10^{-6} = 1.45 \times 10^{-6}$$

As a region of uniform water content and a thickness of 1 km is assumed, the integral of Eq. (5.24) simplifies to become the product of $(m_c - 1)$ and 1000 m so that $AR = 0.145$ cm. For $f = 10$ GHz, $n_c = 8.2 - j1.8$ and the value of AR is 0.144 cm, while for $f = 30$ GHz $n_c = 6 - j2.8$ but AR is still about 0.144 cm. The excess range delay in this case is quite insensitive to the values of index of refraction of water n_c and frequency as the index appears in both the numerator and denominator of the expressions for the index of refraction of the medium, m_c , as in Eq. (5.13) where $Kc = n_c^2$. Using the figure of 0.145 cm for a cloud thickness of 1 km and a vertical path but **considering** instead a cloud 4 km thick and a path at an elevation angle of 10 deg gives a delay of $(4)(0.145)/\sin 10 \text{ deg} = 3.34$ cm, which begins to be more impressive. Also while the water content of 1 g/m³ assumed above is that of a rather dense cloud, the **maximum** water content has been reported to lie between about 6 and 10 g/m³.

Raindrops are considerably larger than the small droplets of clouds, and one must generally use Mie scattering theory or refinements of it for analyzing the effects of raindrops. The technique of deriving an equivalent index of refraction m_c for the medium, however, can still be employed. This approach has been utilized most extensively for determining the attenuation constant for rain but can be used to determine $m_r - 1$ as well. Tables giving values of $m_r - 1$ have been provided by Setzer (1970), and Zufferey (1972) has presented such values in graphical form (Fig. 4.3a). Setzer's value for $m_r - 1$ for a rain of 25 mm/h at a frequency of 3 GHz, for example, is 1.8×10^{-6} . The excess range delay in a 1 km path of uniform rain of that rate is 0.18 cm, a value comparable to that for a path through a cloud 1 km in length. Considering a height extent of rain of 4 km, a path at an elevation angle of 10 deg, and rain of 25 mm/h leads to a possible delay of about 4.15 cm. In contrast with attenuation in rain which increases with frequency up to about 150 GHz, excess range delay due to rain decreases above 10 GHz and stays nearly constant below 10 GHz to 1 GHz but with

modest maxima in the 6 to 10 GHz range, depending on rain rate (Fig. 4.3a). It appears that the excess range delay in some cases of extensive dense fog or cloud and in some heavy rainstorms may be of significance.

5.2 SAND, DUST, AND OTHER PARTICULATE

Sand and dust storms may reduce visibility to 10 m or less, reach a height of 1 km or more, and extend for hundreds of kilometers over the Earth's surface. Based on extrapolation of laboratory measurements at 10 GHz by Ahmed and Auchterlone (1975), it has been estimated that the attenuation constant for a particulate density of 10 g/m^3 is less than 0.1 dB/km for sand and 0.4 dB/km for clay (CCIR, 1986a). It was concluded that total attenuation along an earth-space path should normally be less than 1 dB.

An analysis by Bashir, Dissanayake, and McEwan (1980) for 9.4 GHz has included the case of moist sandstorms and, assuming oblate spheroidal particles, has provided different values of attenuation for horizontal and vertical polarizations. Values for attenuation for moist sandstorms were as high as 1.83 dB/km for horizontal polarization. For dry sand the values were about 0.27 dB/km. Values for particulate density per cubic m of air were not given, but information on particle volumes was included. If the particles themselves have densities of 1 g/cm^3 , the particulate densities or loading in air would be about 1 g/m^3 . Thus particulate densities in the order of 1 to 10 g/m^3 have been assumed for obtaining estimates of attenuation in the cases cited here. Bashir et al. (1980) concluded that attenuation in sandstorms could be a problem for domestic-satellite services in desert areas if sandstorms were encountered at both of two earth stations that were communicating via satellite. The problems of depolarization and interference due to scatter in undesired directions were also considered. The effect of sand storms on microwave propagation

has also been analyzed by Chu (1979) and Ghobrial (1980), and Goldhirsh (1982) has presented a unified, quantitative treatment of the effect of dust storms over desert regions on radar operations. The attenuation constant for propagation through dust or sand storms at centimeter wavelengths, as presented by Ghobrial and repeated by Goldhirsh is

$$\alpha_p = \frac{1.029 \times 10^6 K_i N}{[K_r + 2]^2 + K_i^2} \sum P_i r_i^3 \quad \text{dB/km} \quad (5.26)$$

where K_r and K_i are the real and imaginary parts of the complex relative dielectric constant of the dust or sand particles, N is the total number of particles per cubic m, λ is the wavelength, and P_i is the probability that the particle radius lies between r_i and Ar_i !

This equation has the form of Eq. (5.18) as modified by use of Eq. (5.20). The effects of sand and dust on radar performance tend to be more serious than for earth-space communications because of the longer paths through sand or dust storms and two-way propagation over such paths.

If optical visibility data and information on particle size are available, estimates can be made of particle density N , taking visibility V_i to be related to attenuation by

$$a. V_i = 15 \quad \text{dB} \quad (5.27)$$

where $a.$ is the optical power density attenuation constant. One must also recognize that for a given fixed size of spherical particle

$$a_o = N C_{ext} \quad (5.28)$$

where C_{ext} is the extinction cross section. In addition use can be made of the normalized cross section $Q_{ext} = C_{ext}/\pi a^2$ where a is particle radius. For optical propagation, Q_{ext} has the value of 2,

indicating that the particle affects propagation over a larger area than its physical cross section (because of diffraction as well as reflection and absorption). Using Q_{ext} , the optical power density attenuation constant is given by

$$a_0 = N Q_{\text{ext}} \pi a^2 = (S Q_{\text{ext}} \pi a^2) / (4/3 \pi a^3) = 0.75 S Q_{\text{ext}} / a \quad (5.29)$$

where S is the fraction of a unit volume occupied by the particles of interest. Converting to dB/m and letting $Q_{\text{ext}} = 2$, the optical constant becomes

$$(\alpha_o)_{\text{dB/m}} = 6.5 S/a = 6.5(4/3 \pi a^3)N/a = 27.23 a^2 N \quad (5.30)$$

from which

$$N = \alpha_o / (27.23 a^2) \quad (5.31)$$

Finally letting $a = 1 S/V_i$

$$N = 0.551 / (V_i a^2) \quad (5.32)$$

Expressing a in dB/km and visibility in km

$$N = 5.51 \times 10^{-4} / (V_i a^2) \quad (5.33)$$

with N the number of particles per cubic meter, V_i the visibility in km, and a the particle radius in meters.

Substituting Eq. (5.33) into Eq. (5.26) and considering only particles of radius a results in

$$\alpha_p = \frac{189}{V_i} \frac{a}{\lambda} \left[\frac{3 K_i}{(K_c + 2)^2 + K_i^2} \right] \quad (5.34)$$

with α_p the microwave attenuation constant in dB/km for propagation through dust and V_i the visibility in km.

Optical data may be available in terms of optical depth τ rather than visibility. In that case it is convenient to have an expression for total attenuation A at microwave frequencies in terms of τ . For this purpose, one can start with Eq. (5.26), as applied to particles of a fixed radius a . Then for N substitute Eq. (5.31) which introduces the optical constant α_o into the equation. Assuming a path of length L and constant conditions along the path, $\alpha_o L = 4.34 \tau$ as α_o is in dB/km. The resulting equation is

$$A_{dB} = 54.67 \frac{\tau a}{\lambda} \left[\frac{3K_1}{(K_r + 2)^2 + K_i^2} \right] \text{ dB} \quad (5.35)$$

where r is now in meters (Smith and Flock, 1986)."

Many aerosols of natural and manmade origin occur in the Earth's atmosphere and might occasionally have a slight effect on telecommunications on a local scale. Two sources of information on aerosols (particulate matter of the atmosphere) are Clouds and Storms by Ludlam (1980) and Man's Impact on the Global Environment (SCEP, 1970). Most interest in such particulate matter is related to air pollution or scientific considerations. Clearly visible clouds of pollen are given off by pine trees during spring windstorms, and pollen from various plants is a source of hay fever. Measurements in the plume of Mt. St. Helens on May 18, 1980 showed that particle number densities about 9.3 km downwind in the 0.01 to 10 μm diameter range were from 4 to 1000 times the number density in the ambient air. For particles $< 2 \mu\text{m}$ in diameter the mass loading was about $9.5 \times 10^{-5} \text{ g/m}^3$ compared with less than 10^{-7} g/m^3 in the ambient air (Hobbs et al., 1981). Even interplanetary space is not completely empty but is permeated by the solar wind and has a dust content of around 10^{-17} to 10^{-8} g/m^3 (Berman, 1979; Halliday and McIntosh, 1980).

5.3 BIOLOGICAL MATTER

Some background concerning the effect of vegetation and other biological matter on radiowave propagation is included in this section. More recent developments involving earth-space propagation are described in Sec. 6.4 of the following Chap. 6, which deals with land mobile satellite systems. Vegetation can have important effects on radio wave propagation. Flocks of birds are essentially large blobs of water as far as effects on radio waves are concerned and they can attenuate and scatter incident waves. Insects as well as birds are readily detectable by radar means and can have an effect on propagation when they occur in large concentrations, as in the case of swarms of insects in Africa.

Propagation through the vegetation of dense forests and jungles has been treated by considering the forest to be a lossy dielectric having a complex relative dielectric constant K_c and complex index of refraction n_c with $n_c^2 = K_c$ and $n_c = n_r - jn_i$. The attenuation constant for propagation in such a medium is $\beta_0 n_i$, where β_0 is the phase constant for empty space. Using an alternative form for K_c , namely $K_c = K(1 - j\tan\delta)$, Tamir (1974) reported that measured values of K range from 1.01 to 1.1 and $\tan\delta$ values range from 0.01 to 0.15.

In addition to a direct path through a section of forest, there may be additional rays as shown in Fig. 5.1. In this model TR is the direct path. Rays incident upon the upper boundary at angles equal to or greater than a critical angle θ_c , measured from the perpendicular to the boundary, experience total reflection and energy may thus reach the receiver by a path such as TABR. Waves which skim over the tree tops following a path like TABR are called lateral waves (Tamir, 1984). Some energy may also be reflected from the ground at S and S' and eventually reach the receiver location. Attenuation on direct paths like TR and reflected paths is very high, and, for other than short paths, propagation is said to be by lateral waves, or by a sky wave for lower frequencies.

Using data from several sources in the frequency range from 100 MHz to 3.3 GHz, LaGrone (1960) found an average excess

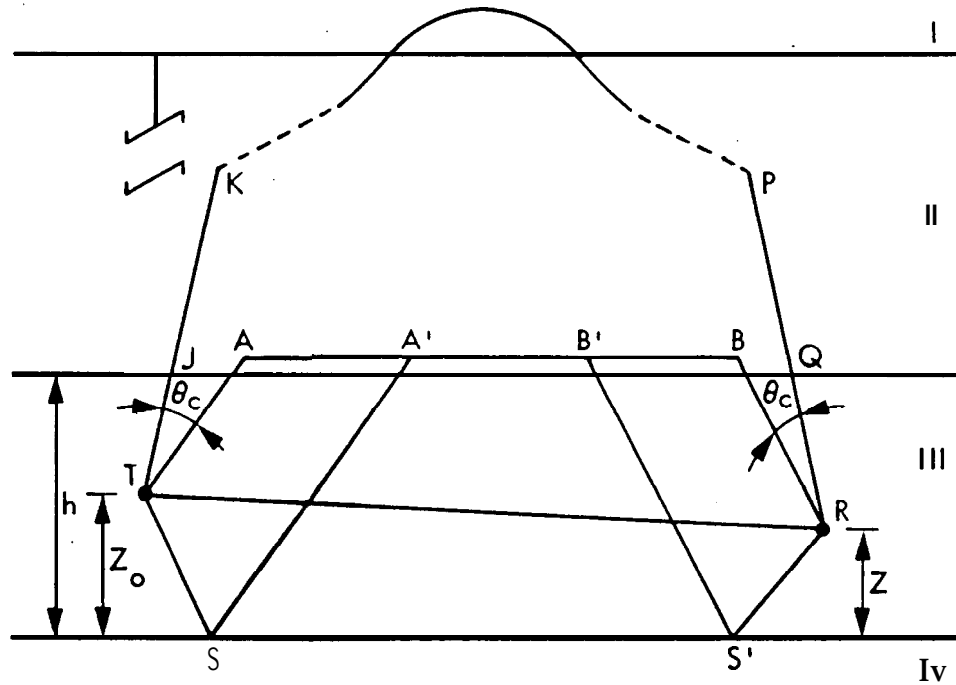


Figure 5.1. Ray paths in an idealized forest environment (Tamir, 1974; CCIR, 1986 b).

attenuation constant α of $1.3 \times 10^{-3} f^{0.77}$ dB/m, with frequency f in MHz, for propagation through woodland. Other data for propagation through woodland in the frequency range from 30 MHz to 2 GHz are summarized in Fig. 5.2 (CCIR, 1986b). For propagation over a grove of trees when transmitting and receiving antennas are sufficiently far from the trees, transmission has been found to be primarily by diffraction (LaGrone, 1977). When antennas are closer to small groves of trees less than 400 m in extent, Weissberger (1981) found a relation for attenuation A in dB which in the rounded form decided upon by the CCIR is

$$A = 0.2 f^{0.3} d^{0.6} \quad \text{dB} \quad (5.36)$$

with frequency f in MHz and distance d in m. The proceedings of a workshop on radio systems in forested and/or vegetated environments contain considerable discussion about propagation in such environments (Wait, Ott, and Telfer, 1974). The paper by

Tamir (1974) on lateral waves and a quite comprehensive though brief paper by Hagn (1974) are included in the proceedings of this workshop. Attenuation by individual trees is described in Sec. 6.4, pages 6-47 and 6-48.

Effects of birds and insects on telecommunications can be expected to be localized. In the near vicinities of breeding and wintering birds and along major migration routes in the spring and fall, concentrations of birds could disrupt communications momentarily. Concentrations of sea birds occur in migration and/or summer in arctic and subarctic areas, including the Aleutian and Pribilof Islands, the Bering Strait, Baffin Island, etc. Wintering areas of waterfowl and cranes in North America include the Gulf Coast, southern New Mexico, and interior valleys of California. The areas of bird concentration are commonly in or near wildlife refuges operated by federal agencies. Contact with the U.S. Fish and Wildlife Service in the United States and the Canadian Wildlife Service in Canada would be advisable if consideration is being given to installations near wildlife refuges or other areas of bird concentration. Huge flocks of blackbirds and starlings are sometimes a problem in towns and cities. Large flocks of birds scatter electromagnetic radiation efficiently and have the potential for causing interference between telecommunication systems and between telecommunication and radar systems.

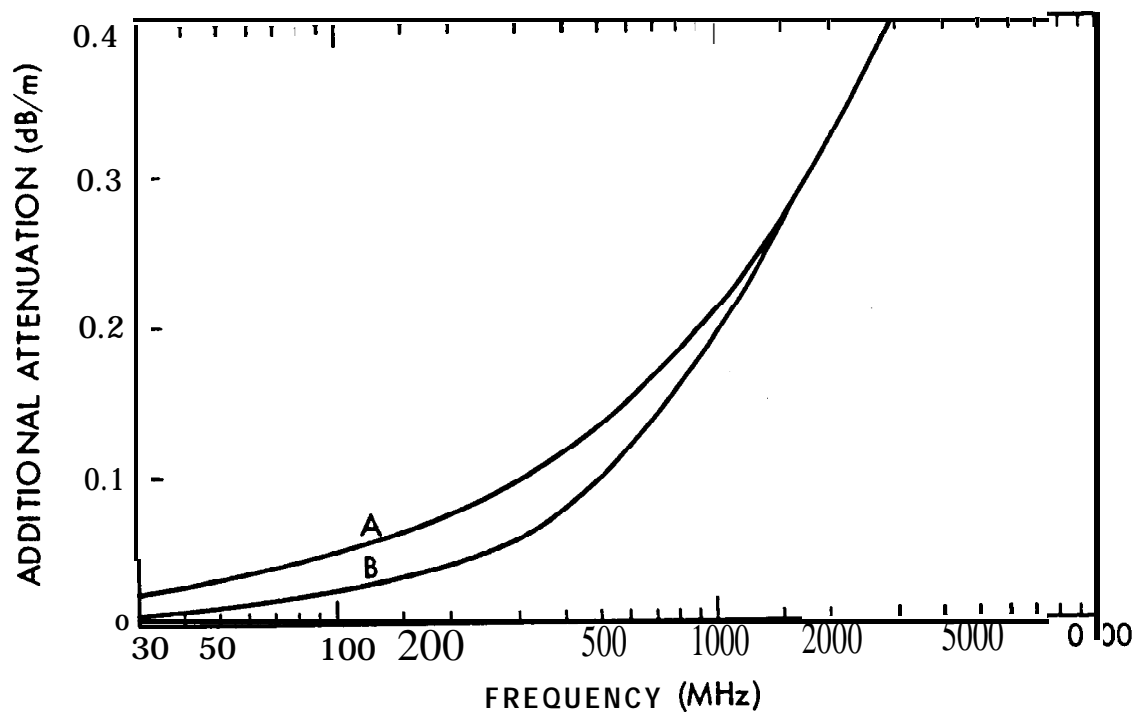


Figure 5.2. Excess attenuation in propagation through woodland (CCIR, 1986 b). A: vertical polarization, B: horizontal polarization.

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